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Inventory of aerosol and sulphur dioxide emissions from India. Part II—biomass combustion

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Abstract

A spatially resolved biomass burning data set, and related emissions of sulphur dioxide and aerosol chemical constituents was constructed for India, for 1996–1997 and extrapolated to the INDOEX period (1998–1999). Sources include biofuels (wood, crop waste and dung-cake) and forest fires (accidental, shifting cultivation and controlled burning). Particulate matter (PM) emission factors were compiled from studies of Indian cooking stoves and from literature for open burning. Black carbon (BC) and organic matter (OM) emissions were estimated from these, accounting for combustion temperatures in cooking stoves. Sulphur dioxide emission factors were based on fuel sulphur content and reported literature measurements. Biofuels accounted 93% of total biomass consumption (577 MT yr^{-1}), with forest fires contributing only 7%. The national average biofuel mix was 56 : 21 : 23% of fuelwood, crop waste and dung-cake, respectively. Compared to fossil fuels, biomass combustion was a minor source of SO_2 (7% of total), with higher emissions from dung-cake because of its higher sulphur content. $PM_{2.5}$ emissions of 2.04 Tg yr^{-1} with an "inorganic fraction" of 0.86 Tg yr^{-1} were estimated. Biomass combustion was the major source of carbonaceous aerosols, accounting 0.25 Tg yr^{-1} of BC (72% of total) and 0.94 Tg yr^{-1} of OM (76% of total). Among biomass, fuelwood and crop waste were primary contributors to BC emissions, while dung-cake and forest fires were primary contributors to OM emissions. Northern and the east-coast India had high densities of biomass consumption and related emissions. Measurements of emission factors of SO_2, size resolved aerosols and their chemical constituents for Indian cooking stoves are needed to refine the present estimates.

Keywords: Biofuels; Forest biomass; Black carbon; Organic matter; INDOEX

1. Introduction

One of the largest uncertainties in the assessment of aerosol–climate interactions arises from biomass combustion emissions (Schwartz and Andreae, 1996; Andreae et al., 1988). Biomass combustion results in emissions of small particles ($D_p < 2.5\,\mu m$) (Ward et al., 1991; Einfeld et al., 1991) with a large carbonaceous fraction (Cooper, 1980; Dasch, 1982; Susott et al., 1991) and inorganic water-soluble ions (Rau, 1989; Allen and Miguel, 1995; Cachier et al., 1991). The two carbonaceous aerosol types are organic carbon (OC), which mainly scatters radiation (Sloane et al., 1991; Novakov and Corrigan, 1996) and cools the atmosphere (direct forcing) and black carbon (BC), which absorbs solar radiation and results in heating of the atmosphere (Haywood and Shine, 1995; Haywood and Ramaswamy, 1998). The water-soluble inorganic ions (e.g. potassium, sodium, sulphate, calcium and magnesium) and hygroscopic organic compounds in biomass combustion particles would act as cloud condensation nuclei (CCN), leading to net reduction of solar radiation received at Earth's surface (indirect forcing) (Penner et al., 1992). Emissions from biomass sources are known to be spatially and temporally inhomogeneous, needing better characterisation.

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Biomass fuels, including wood, crop waste and dung-cake account for 47% of the total energy consumption in India (TEDDY, 1997; Ravindranath and Hall, 1995) and are the major source (85–90%) of cooking-energy in rural India (TEDDY, 1997). The 1990 national consumption of biofuels was estimated at about $450\,MT\,yr^{-1}$ with a 59 : 18 : 23% division among fuel-wood, dung-cake and crop waste, respectively. Biomass burning also results from controlled and accidental forest fires (Prasad et al., 2000; Joshi, 1991). In addition, forest biomass is burnt for agricultural land clearing and a fraction of crop waste is fired in fields following harvest.

Some research efforts have addressed emissions from biomass combustion in India, as part of global emission inventories (Liousse et al., 1996; Cooke and Wilson, 1996; Spiro et al., 1992) and regional studies for south and southeast Asia (Arndt et al., 1997; Streets and Waldhoff, 1998; Akimoto and Narita, 1994; Kato and Akimoto, 1992). The approach in these has been to use national-average per-capita consumption of biofuels in rural India (Joshi et al., 1991; TEDDY, 1995). These did not include regional variations in biofuel availability and consumption, which result from variations in climate, soil type and cropping patterns. The rural population density for the base year of concern (1984–1990) was used for spatially distributing the fuel use and emissions, and an update of the base year is needed. Urban biofuel use was estimated based on several assumptions like urban-slum population being the users, and per capita consumption being a function of the reported rural use (Streets and Waldhoff, 1998). Assumptions were also made of the fraction of crop waste burnt in field and that used for energy in cooking stoves (e.g. Liousse et al., 1996). Some global inventories (Cooke and Wilson, 1996; Liousse et al., 1996; Spiro et al., 1992) included forest and grassland burning for India, based on tropical Asia average values of Hao et al. (1990), or national average values for India (Joshi, 1991). The assumptions used in the biomass combustion estimates, both in terms of their amount and spatial distribution, have a high degree of uncertainty in them. The emission factors used to multiply biomass consumption and obtain emissions have also been derived using many assumptions. Biofuels are burnt in small, open-chamber, natural-draft stoves (*chulhas*), used widely for cooking in rural India, and there are very few measurements of emissions from these sources (Ahuja et al., 1987; Joshi et al., 1989, 1991). Previous inventories have arrived at a best approximation of emission factors for pollutants like sulphur dioxide (SO_2), BC and organic matter (OM) from limited measurements reported for similar sources. These are from wood burning in fire-places or space-heating stoves in developed countries (Cooper, 1980; Butcher and Sorenson, 1979; Dasch, 1982; Butcher and Ellenbecker, 1982) from wind-tunnel experiments of crop waste burning and elephant-dung pellet combustion (Jenkins et al., 1991, 1993; Liousse et al., 1996). Use of emission factors measured for other combustion systems would also introduce uncertainties in the estimated emissions.

Recent estimates of national level SO_2 and aerosol emissions, for India, indicate the importance of biomass combustion contribution to SO_2, particulate matter ($PM_{2.5}$) $<2.5\,\mu m$ diameter, BC and OM (Venkataraman et al., 1999; Reddy and Venkataraman, 1999, 2000). During the recently completed Indian Ocean Experiment (INDOEX, 1998–2000) campaign, low aerosol single scattering albedo were observed over the Indian Ocean (Müller et al., 2001a, b), and absorbing aerosols (e.g. BC) are believed to have originated from India from biomass combustion (Müller et al., 2001a, b).

A comprehensive inventory for SO_2 and aerosols from the biomass combustion for India for a recent base year is needed as input to the regional scale climate-modelling studies over India and Indian Ocean during INDOEX period. The objectives of the paper are (i) construction of a spatially resolved biofuel and biomass combustion data set for India for 1996–1997, (ii) development of realistic emission factors of SO_2 and aerosols to represent biomass burning in domestic cooking stoves and forests, (iii) construction of a spatially resolved ($0.25^\circ \times 0.25^\circ$) emission inventory for SO_2 and aerosol chemical constituents from biomass combustion in India and projection of the emissions to the INDOEX period (1998–1999).

2. Method

In India, biomass combustion includes fuel for domestic cooking in stoves (henceforth referred to as biofuels), forest fires and open burning of crop waste after harvest. Biofuels used in rural India include wood, crop waste and dung-cake (Fig. 1). The per capita consumption of different biofuels at district level was derived from the rural energy database (REDB), developed by Tata Energy Research Institute (Joshi et al., 1992; Sinha et al., 1998). The biofuel consumption in each district was estimated by multiplying the per capita consumption with the district rural population for 1996–1997 from census data. The base year 1996–1997 was chosen to estimate the emissions for the same year as emissions from fossil fuel combustion (*see companion paper*). Wood is the only reported biofuel used in urban areas. The state average per capita wood consumption (NSS, 1996) and district urban population were used to estimate urban fuelwood consumption at the district level. District wise forest biomass burning was calculated from forest cover statistics (FSI, 1998), the area depleted by forest fires and combustion efficiencies (Joshi, 1991). Emission factors of SO_2 and

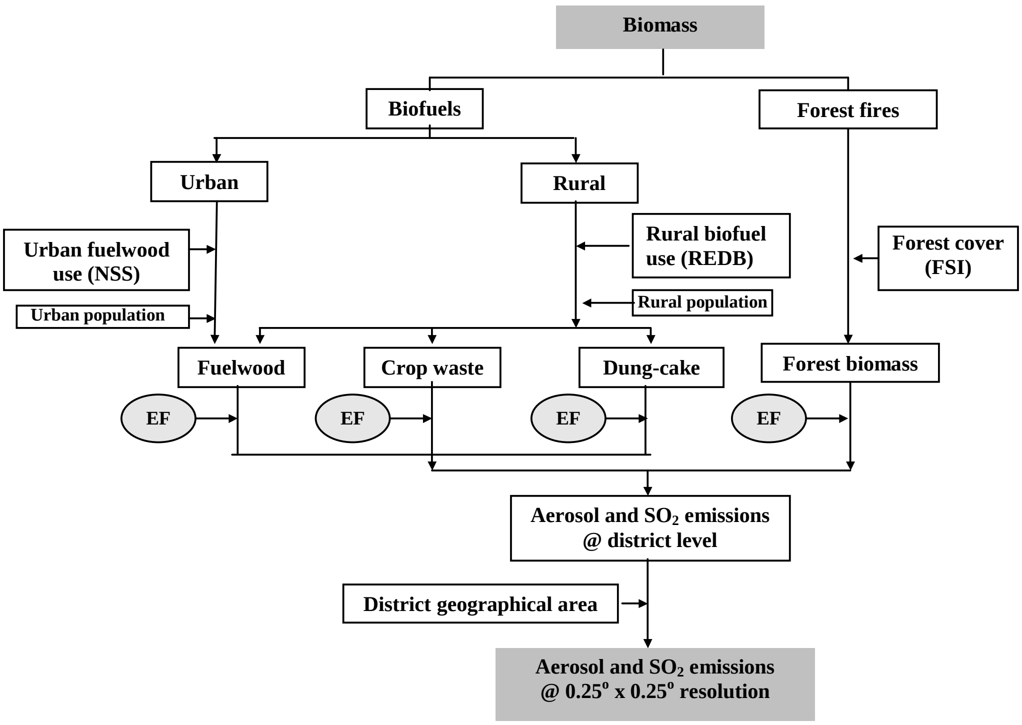

Fig. 1. Methodology for constructing a spatially resolved aerosol and sulphur dioxide emissions inventory from biomass combustion.

aerosol chemical constituents for biofuels and forest fires were derived from reported measurements. Emissions were estimated as product of biomass consumption and corresponding emission factors in each district.

As in the *companion paper* on fossil fuel combustion, the estimated district biomass consumption and emissions (SO_2 and aerosols), were converted to consumption density and emission fluxes (mass per unit area), using district geographical area and assigned to corresponding grids (Fig. 1). While, the biofuel consumption and resulting emissions vary temporally, due to lack of data on the seasonal variation, we assumed uniform consumption and resulting emissions throughout the year. In India, most forest fires occur between January and July (Joshi, 1991), and emissions from forest fires were distributed uniformly between these months.

3. Biomass consumption data

3.1. Biofuels

3.1.1. Rural areas

The eating habits in an Agrarian rural society and, therefore, cooking-energy requirements and fuel mix are likely to be determined by the availability of biomass and the cropping patterns. Cropping patterns, in turn, are likely to have evolved in response to agro-climatic conditions, most influential of which would be the soil quality, temperature and availability of water for agriculture. These are the major variables, for classification of India into 15 agro-climatic regions for agricultural planning by the Planning Commission of Government of India (Planning Commission, 1989). A REDB was constructed by post-stratifying the available rural energy consumption surveys to agro-climatic regions (Joshi et al., 1992; Sinha et al., 1998). The energy surveys were conducted during 1984–1992, by various agencies sponsored by Ministry of Non-conventional Energy Sources (MNES). These surveys include 638 villages covering 39,000 households in 201 districts spread over 17 states and over 14 of the 15 agro-climatic regions of India. The survey results include energy for cooking, agriculture and other parameters used for future rural energy planning (e.g. land categories, land ownership, crop yields and prices, etc.). Assuming that biofuel consumption (wood, crop waste and dung-cake) is constant within an agro-climatic region, average per capita consumption was derived from the REDB. Districts which fall in each agro-climatic region were identified (Planning Commission, 1989; GoI, 1992) and assigned the respective per capita consumption of each biofuel. These were used, along with 1996–1997 district wise rural population, to estimate biofuel consumption at the district level. Rural population for mid 1996–1997, was extrapolated from 1991 census, using the district rural population decennial growth rate during 1981–1991, which was assumed to apply for 1991–2001 (GoI, 1992, 1998).

3.1.2. Urban areas

The only biofuel use reported in urban India is fuelwood (NSS, 1996). The 12th national sample survey (NSS) of consumer expenditure includes per capita consumption of fuelwood and fraction of urban population using fuelwood. NSS results are given as state average per capita consumption. Using 1996–1997 district urban population, district wise urban fuelwood consumption was estimated. Once again, urban population for mid 1996–1997 was extrapolated from the 1991 census (GoI, 1992, 1998).

3.2. Forest biomass

In India, forest maintenance is carried out through working plans covering approximately 78% of total forest area (Mo and Mo, 1987). Using forest cover statistics (FSI, 1998) and state wise average percentage of area covered under working plans (Mo and Mo, 1987), forest area covered under working plans was calculated for 1995–1997. The Forest Survey of India (FSI) reports bi-annual district wise forest cover and its net change during last two years from accidental fires and shifting cultivation (FSI, 1998). Districts with net loss of forest cover during 1995–1997 were identified and this was apportioned equally to each year. Apart from the above, forest biomass is burned for natural regeneration and fire prevention resulting in partial loss of forest cover, reported at 3.0% and 2.6%, respectively (Joshi, 1991), applied as a national average to all districts. In addition, Joshi (1991) reports dry mass above ground for Indian forests at $5.2\,\mathrm{kg\,m^{-2}}$ and a burn efficiency of 80% and 10%, for accidental fires/shifting cultivation and controlled burning, respectively. Using these assumptions, forest biomass burnt from accidental fires, shifting cultivation and controlled burning was estimated for each district. While these estimates are for 1995–1997, there would not be any systematic trend of increase or decrease in the forest fires over a period of time, and we use these data for 1996–1997.

4. Emission factors

4.1. Sulphur dioxide

Sulphur dioxide emissions from biomass combustion depend on the sulphur content of biomass, combustion temperatures and the amount of sulphur retained in the ash and/or char. The reported average sulphur content of fuelwood and dung-cake are 0.04% and 0.07%, respectively (Table 1) (Smith et al., 2000; CIGR, 1999). There are few measured sulphur dioxide emission factors for biofuel combustion, and only one study reports SO_2 emission factors for wood combustion in residential cooking stoves (Ballard-Tremeer, 1997; Ballard-Tremeer and Jawurek, 1996). These emission factors range from 0.1 to $1.0\,\mathrm{g\,kg^{-1}}$ with an average of $0.48\,\mathrm{g\,kg^{-1}}$. Chemical analysis of char and ash showed sulphur contents of 0.03% and 0.08% (percentage sulphur by mass), respectively, and it was reported that about 60% of sulphur in the fuel converts into SO_2 with the remainder in ash and/or char. The average sulphur content of crop waste (0.04%) (Smith et al., 2000) is similar to fuelwood and the emissions factor, in the absence of reported measurements, was assumed same as for wood. The sulphur content of forest biomass (0.04%) is similar to wood (CIGR, 1999), and once again the same emission factors were assumed (Table 1). The reported average sulphur content of dung-cake (0.07%) is higher than wood. We assumed 60% of sulphur in the fuel is converted to SO_2, as reported for wood combustion (Ballard-Tremeer, 1997; Ballard-Tremeer and Jawurek, 1996), resulting in an emission factor of $0.86\,\mathrm{g\,kg^{-1}}$ (Table 1).

4.2. $PM_{2.5}$ and chemical constituents

4.2.1. $PM_{2.5}$ aerosols

The PM emissions from cooking stoves vary considerably depending on the fuel type, stove design and combustion parameters (Joshi et al., 1989, 1991). Reported measurements of average PM emission factors for wood, crop waste and dung-cake burning in Indian cooking stoves are 1.9, 4.9 and $6.3\,\mathrm{g\,kg^{-1}}$, respectively (Joshi et al., 1989, 1991; TERI, 1987). Using a reported $PM_{2.5}$/PM ratio of 0.80, from wood and crop waste burning experiments (Jenkins et al., 1993; Radke et al., 1991, 1988; Dasch, 1982), $PM_{2.5}$ emission factors were

Table 1
Sulphur content and SO_2 emission factors for biomass sources

Fuel	S content (%)	SO_2 emission factor ($\mathrm{g\,kg^{-1}}$)
Fuelwood	0.04	0.48[a]
Crop waste	0.04	0.48[b]
Dung-cake[c]	0.07	0.84[c]
Forest biomass[b]	0.04	0.48[b]

[a] Measured for wood combustion in cooking stoves (Ballard-Tremeer, 1997; Ballard-Tremeer and Jawurek, 1996).

[b] Assumed same as fuelwood.

[c] Derived assuming 60% of sulphur in the fuel convert into SO_2.

Table 2
Aerosol chemical constituents emission factors for biomass combustion

Biomass type	Emission factor ($g\,kg^{-1}$)			
	$PM_{2.5}$	Black carbon	Organic matter	"Inorganic fraction"
Fuelwood	1.50	0.41	0.35	0.75
Crop waste	3.88	0.47	0.91	2.51
Dung-cake	5.04	0.25	3.47	1.32
Forest biomass	13.61	0.98	7.96	4.67

calculated. The measured average PM emission factor for open forest burning is much higher at $16.5\,g\,kg^{-1}$, with 83% of mass below 2.5 μm diameter (Ward et al., 1991; Patterson and McMahon, 1984; Patterson et al., 1986) (Table 2).

4.2.2. Carbonaceous aerosols

The PM emissions from biomass combustion primarily consist of carbonaceous aerosols and water-soluble inorganic ions (Rau, 1989). Carbonaceous aerosols are of two types, BC with a H/C molar ratio from 1 to 8 and OM with H/O associated resulting in an OM to OC ratio of ~ 1.3. BC/OM ratio depends upon the combustion temperature, with low-temperature, resulting in greater OM formation (Rau, 1989).

A $BC/PM_{2.5}$ ratio of 0.27 (Rau, 1989) for wood burning in residential heating stoves (combustion temperatures of $600 \pm 100°C$) was applied for Indian cooking stoves which have similar combustion temperatures ($528 \pm 32°C$) (Venkataraman and Rao, 2001). The BC fraction of PM emissions from crop waste ranges 0.08–0.16 depending on the type of waste and burning conditions (Liousse et al., 1996) and we used an average value of 0.12 for crop waste as biofuel. A $BC/PM_{2.5}$ ratio of 0.05 for dung-cake was used from Liousse et al. (1996). An average reported $BC/PM_{2.5}$ ratio of 0.074 was used for open forest burning (Susott et al., 1991; Ward et al., 1991; Einfeld et al., 1991; Patterson and McMahon, 1984; Patterson et al., 1986).

For wood and crop waste combustion, an average $OC/PM_{2.5}$ of 0.18 was assumed, as reported for hot burning conditions (Rau, 1989). Dung-cake is usually packed in a stove or pit on the ground and fired, resulting in smouldering combustion and limited oxygen transfer, and likely lower combustion temperatures. For dung-cake, we used an average $OC/PM_{2.5}$ ratio of 0.54, measured for cool burning conditions (Rau, 1989). An average $OC/PM_{2.5}$ ratio of 0.45 was reported for open forest burning (Susott et al., 1991; Ward et al., 1991; Einfeld et al., 1991; Patterson and McMahon, 1984). To account for hydrogen, oxygen and other species in the carbonaceous aerosols, OM to OC ratio of 1.3 was assumed, for all biomass types (Countess et al., 1981; Liousse et al., 1996).

4.2.3. The "inorganic fraction" of $PM_{2.5}$

Biomass combustion aerosol emissions consists of carbonaceous matter along with an "inorganic fraction" primarily containing water-soluble inorganic ions (e.g. potassium, calcium, sulphate, etc.) and mineral ash (Rau, 1989; Allen and Miguel, 1995; Cachier et al., 1991). Water-soluble inorganic ions accounted for 10–20% mass of wood combustion aerosols with potassium alone contributing 6–13% (Rau, 1989). In the present estimates the difference of $PM_{2.5}$ and carbonaceous aerosols (sum of BC and OM) was assumed to be the "inorganic fraction" (Table 2).

5. Biomass consumption

5.1. Biofuels

Rural and urban biofuel consumption were estimated using respective per capita consumption at a district level, and results aggregated at the state and national level. Total biofuel (all fuels) consumption was $538\,MT\,yr^{-1}$ for 1996–1997. Rural fuelwood consumption was $293\,MT\,yr^{-1}$, with the states of Madhya Pradesh, Bihar, Orissa, Andhra Pradesh and West Bengal accounting 51% of total consumption. Urban fuelwood consumption was very low ($9\,MT\,yr^{-1}$). Crop waste consumption was $116\,MT\,yr^{-1}$, with east-coast states (Tamil Nadu, Andhra Pradesh, Orissa and West Bengal) contributing 50% of the total. The estimated dung-cake consumption was $121\,MT\,yr^{-1}$ (Fig. 2) with Uttar Pradesh alone contributing $40\,MT\,yr^{-1}$. The central and west-coast states have lower per capita consumption and moderate population densities resulting in lower consumption of biofuels. There is a wide variation in the fuel mix from region to region, with a national average of 56 : 21 : 23% for wood, crop waste and dung-cake, respectively. The largest contribution to biofuel consumption is from Uttar Pradesh (13%, dung-cake—7%; fuelwood—4%;) followed by Andhra Pradesh (11%, fuelwood—5%; crop waste—4%;), Bihar (10%, fuelwood—7%; dung-cake—1%) and Madhya Pradesh (9%, fuelwood—7%; dung-cake—1%;).

Fuelwood consumption density was higher ($>150\,t\,km^{-2}$) in the eastern India and central parts of northeast states (Fig. 3a). The higher per capita consumption of fuelwood in the eastern plateau and hills (eastern Madhya Pradesh, Orissa and Bihar), and eastern Himalayan region (West Bengal) and high population density in the mid Gangetic region (Bihar) resulted in the higher density of consumption. The lowest consumption densities ($<50\,t\,km^{-2}$) were estimated for the western Himalayan region (lower

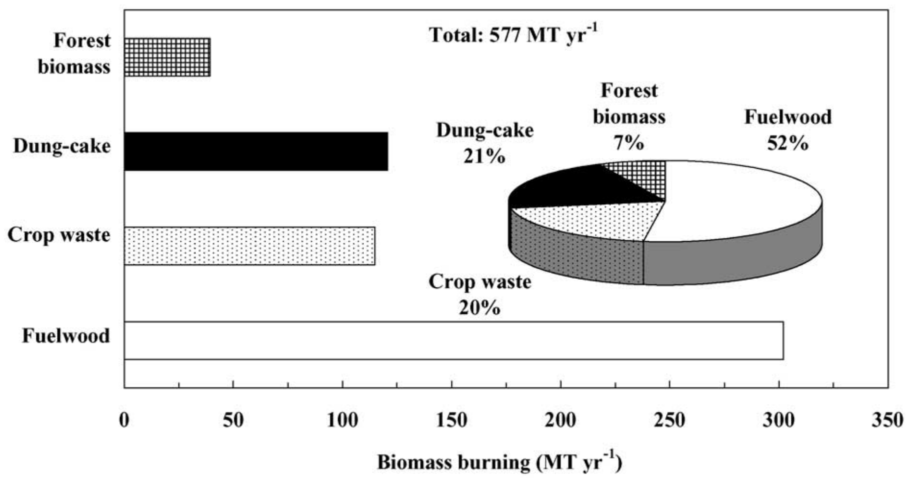

Fig. 2. Biomass burning estimates for India, for 1996–1997. Biofuels account 93% of total, with forest fires contributing only 7%.

population density), western Rajastan (lower per capita consumption and population density). Moderate consumption intensities (50–150 t km^{-2}) were seen in the rest of India. Only east-coast India (Tamil Nadu, Andhra Pradesh, and Orissa) had high (150–300 t km^{-2}) crop waste consumption density due to the highest per capita consumption, accounting for 47% of total consumption (Fig. 3b). Southern India (“southern plateau region”) had moderate densities (50–150 t km^{-2}), and remaining parts of India had lower values ($<$25 t km^{-2}). The dung-cake consumption intensity in the Uttar Pradesh was highest ($>$150 t km^{-2}) (Fig. 3c) from higher per capita consumption and population density. The “east-coast plains and hills” showed moderate densities (resulting from moderate per capita consumption) and rest of India had low densities.

5.2. Forest biomass

Total forest biomass burned was 39 MT yr^{-1}, accounting for only 7% of the total biomass burning in India (Fig. 2). Accidental fires/shifting cultivation accounted 70% and controlled fires accounted 30% of total forest biomass. Madhya Pradesh (43%), Andhra Pradesh (24%), Orissa (7%) and Maharashtra (4%) together contributed 78% of the total mostly from accidental fires/shifting cultivation. The forest biomass burning was high in the two districts of Andhra Pradesh (Vishakapatnam, Vizianagaram) and east Madhya Pradesh ($>$150 t km^{-2}) (as these two states account 40% of total) (Fig. 3d). Moderate biomass burning was observed in parts of Andhra Pradesh and Maharashtra, northeastern states of Nagaland and Manipur, and rest of India had low values ($<$25 t km^{-2}).

Biofuel consumption increased by 20%, 16% and 14%, for wood, crop waste and dung-cake, respectively, between 1990 (Sinha et al., 1998) and 1996–1997. This increase reflects only population growth, because the per capita consumption used was the same for the previous and current estimates. Refinements in the present estimate include district level population growth, regional variations in fuel-consumption and fuel-mix, resulting in more realistic consumption and spatial distribution. In previous regional (Asia) emission inventories, biofuel consumption for India was 375 MT yr^{-1} for 1988 (Arndt et al., 1997) and 499 MT yr^{-1} for 1990 (Streets and Waldhoff, 1998), compared to the present estimate of 538 MT yr^{-1} for 1996–1997. The somewhat higher estimates in the previous studies are partially due to the inclusion of crop waste and dung-cake in urban areas. However, crop waste and dung-cake use as biofuel in urban areas contributes only 3.5% of total biofuel consumption in India (Joshi, 1991).

6. Pollutant emissions

6.1. Sulphur dioxide emissions

The estimated SO_2 emissions from biomass combustion from India for 1996–1997 are 0.32 Tg SO_2 yr^{-1}, only 7% of the total, with balance emissions from fossil fuel combustion (*see companion paper*). Biofuels account for 94% and forest fires 6% of SO_2 emissions from biomass combustion from India (Table 3). The highest contribution is from fuelwood (45%), followed by dung-cake (32%) and crop waste (17%). High sulphur content of dung-cake results in higher SO_2 emissions compared to other biomass types.

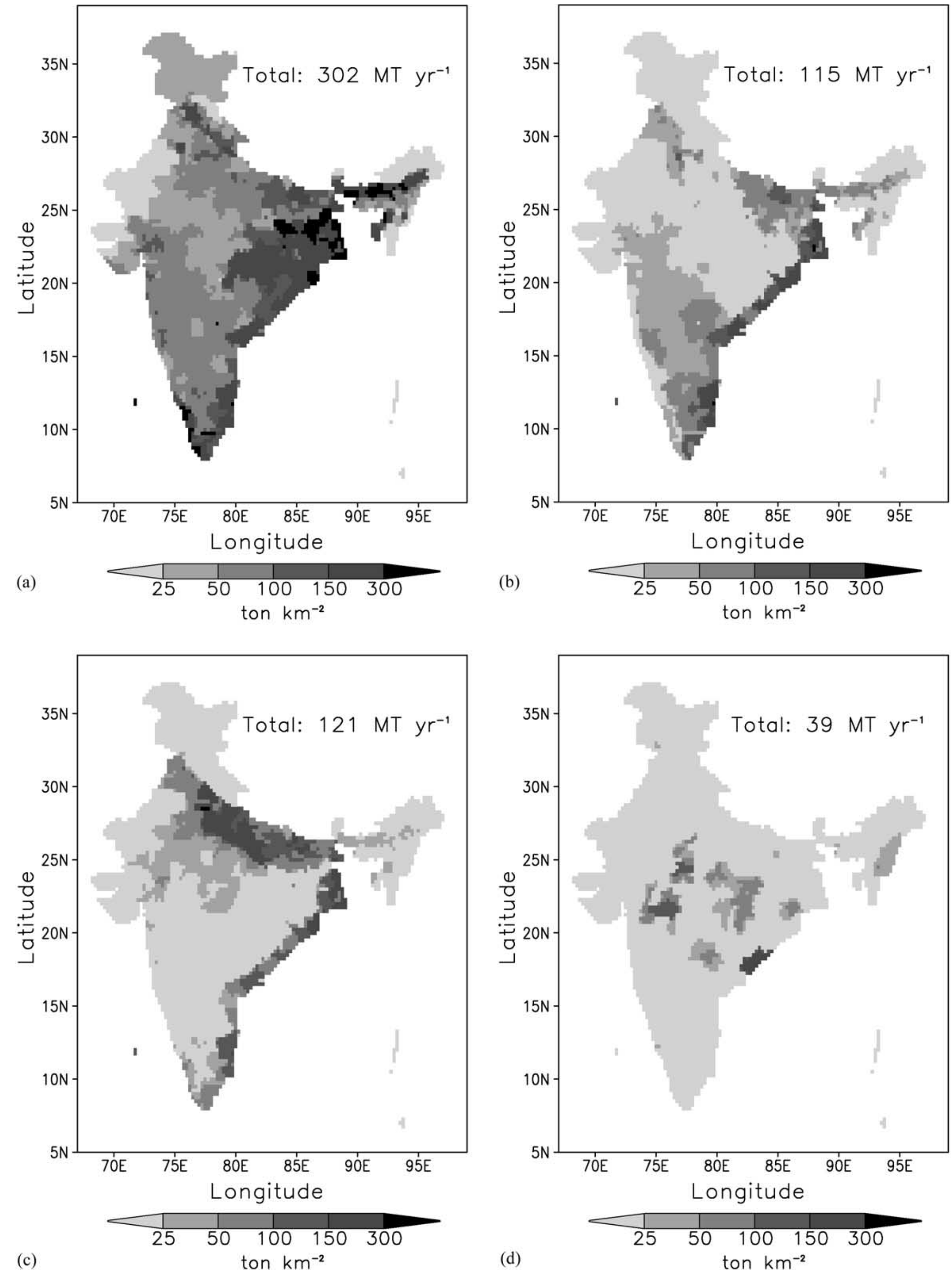

Fig. 3. Spatial distribution of biomass consumption in India for 1996–1997; (a) fuelwood, (b) crop waste, (c) dung-cake, (d) forest biomass.

Table 3
Summary of SO_2 and aerosol emissions from biomass combustion from India for 1996–1997

Biomass type	SO_2 and aerosol emissions ($Gg\,yr^{-1}$)				
	SO_2	$PM_{2.5}$	Black carbon	Organic matter	"Inorganic fraction"
Fuelwood	145 (45)[a]	454 (22)	123 (50)	106 (11)	225 (26)
Crop waste	55 (17)	446 (22)	54 (22)	104 (11)	288 (34)
Dung-cake	101 (32)	608 (30)	30 (12)	419 (45)	159 (19)
Forest biomass	19 (6)	535 (26)	39 (16)	313 (33)	184 (21)
Total	320 (1 0 0)	2044 (1 0 0)	245 (1 0 0)	943 (1 0 0)	856 (1 0 0)

[a] Values in parenthesis are relative contribution to respective pollutant emissions (%).

Table 4
Summary of SO_2 emission inventories for biomass combustion in India

Reference	Base year	SO_2 emissions (Tg $SO_2\,yr^{-1}$)	% of total SO_2 emissions
This study	1996–1997	0.32	7.0
Garg et al. (2001)[a]	1990	0.16	4.5
	1995	0.28	6.0
Venkataraman et al. (1999)	1990	0.94	23
Streets and Waldhoff (1998)[a]	1990	0.88	—[b]
Arndt et al. (1997)[a]	1987–1988	0.91	19

[a] Only biofuels.
[b] SO_2 emission estimates are only for biofuels combustion.

These SO_2 emissions for 1996–1997 are a factor of about three lower than previous estimates for 1987–1988/1990 (Venkataraman et al., 1999; Arndt et al., 1997; Streets and Waldhoff, 1998) (Table 4). Higher SO_2 emission estimates by Venkataraman et al. (1999) resulted from use of high constant emission factor of $1.54\,g\,kg^{-1}$. Though SO_2 emission factors used by Arndt et al. (1997) and Streets and Waldhoff (1998) for fuelwood and crop waste are comparable with present values, use of very high value of $6.0\,g\,kg^{-1}$ for dung-cake (factor of seven higher than present value) resulted in higher SO_2 emissions, accounting 75% of their total SO_2 emissions (0.91–0.94 $Tg\,yr^{-1}$) from biofuel combustion. However, the value used by Arndt et al. (1997) and Streets and Waldhoff (1998) would greatly exceed the measured sulphur content (0.07%) of the dung-cake. The present emission factors, based on measurements for wood burning in domestic cooking stoves and sulphur content of the fuels, would most closely represent SO_2 emissions from biofuel combustion in Indian cooking stoves. Our national SO_2 emissions compare well with the recent estimate of Garg et al. (2001) of 0.28 $Tg\,yr^{-1}$ for 1995. While previous estimates had placed the biomass burning contribution to SO_2 emissions at 19–23% (Arndt et al., 1997; Venkataraman et al., 1999), this estimate, of 7% contribution, is more realistic because of the new emission factors, especially for dung-cake combustion.

SO_2 emissions are highest from Uttar Pradesh (15%) followed by Andhra Pradesh (11%), Madhya Pradesh (11%) and Bihar (11%), together accounting 48% of total emissions. Higher emissions from Uttar Pradesh are from dung-cake, Madhya Pradesh from fuelwood and forest biomass, Andhra Pradesh from all biofuels and Bihar from fuelwood combustion. SO_2 emission fluxes (>250 kg $SO_2\,km^{-2}$) are highest in parts of Uttar Pradesh, West Bengal and east-coast (Orissa, Andhra Pradesh, Tamil Nadu), which have high biofuel consumption (Fig. 4). Moderate to high emission fluxes (100–250 kg $SO_2\,km^{-2}$) estimated over entire east-coast, remaining parts of Uttar Pradesh and Assam. The west-coast states and central India experience lower emission fluxes of 25–100 kg $SO_2\,km^{-2}$. The western Rajasthan, Jammu & Kashmir, Arunachal Pradesh and Mizoram have the lowest emission fluxes (<25 kg $SO_2\,km^{-2}$), because of low biomass consumption.

6.2. Emissions of $PM_{2.5}$ and chemical constituents

6.2.1. $PM_{2.5}$ emissions

$PM_{2.5}$ emissions from biomass combustion from India for 1996–1997 are 2.04 $Tg\,yr^{-1}$, comparable to that from

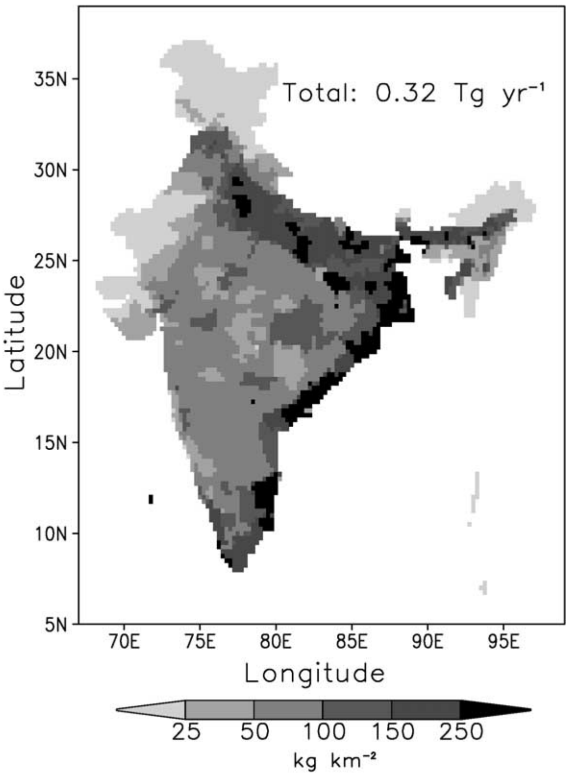

Fig. 4. Spatial distribution of SO_2 emissions from biomass combustion.

fossil fuel combustion (2.00 Tg yr^{-1}, *see companion paper*), making biomass combustion a significant source of $PM_{2.5}$ emissions. While $PM_{2.5}$ emissions from fossil fuel combustion are primarily from coal combustion in large point sources (e.g. power plants) and localised, emissions from biomass combustion are area sources spread all over India. The highest relative contribution to $PM_{2.5}$ emissions from biomass combustion is from dung-cake (30%) followed by forest fires (26%), fuelwood (22%) and crop waste (22%) (Table 3). Dung-cake and crop waste resulted in higher emissions in comparison to fuelwood, because of high emissions factors. While the forest fires account only 7% of the consumption, they contribute 26% of the $PM_{2.5}$ emissions, because of the higher emission factors for open burning than combustion in cooking stoves.

The highest $PM_{2.5}$ emissions are estimated from Madhya Pradesh (0.35 Tg yr^{-1}) followed by Andhra Pradesh (0.31 Tg yr^{-1}) and Uttar Pradesh (0.29 Tg yr^{-1}), together accounting 46% of total emissions. The forest fires in Madhya Pradesh, crop waste and forest fires in Andhra Pradesh and dung-cake in Uttar Pradesh are responsible for higher emissions. The Vishakapatnam and Vizianagaram districts of Andhra Pradesh have highest $PM_{2.5}$ emissions (>3000 kg km^{-2}) from forest fires. Grids with high emissions (500–1500 kg km^{-2}) are mostly centralised in Uttar Pradesh, Bihar, eastern Madhya Pradesh, east-cost India (Orissa, Andhra Pradesh, Tamil Nadu), Kerala and northeast states. In Uttar Pradesh and Bihar, emissions are primarily from dung-cake, whereas in east-Madhya Pradesh from forest fires. Though the highest contribution to $PM_{2.5}$ emissions is from Madhya Pradesh, emissions are concentrated only in the eastern part of the state. In the northeast states, high per capita consumption of fuelwood yields PM emissions. Once again, western Rajastan and Jammu & Kashmir experience lowest emissions, with lower population densities (low biofuel consumption) and low forest cover.

6.2.2. Carbonaceous aerosol emissions

The BC emissions from biomass combustion are 0.25 Tg yr^{-1} and account for 71% of the total BC emissions from India, with most of the balance from diesel vehicles (*see companion paper*). Largest contributors to BC emissions are fuelwood and crop waste accounting 72% of BC emissions (Table 3) from biomass combustion. While, dung-cake contribution to $PM_{2.5}$ was 30%, because of lower BC fraction of particulate emissions from dung-cake, it results in lower BC emissions than fuelwood and crop waste. The OM emissions from biomass combustion are 0.94 Tg yr^{-1}, contributing 76% of total OM emissions from India, with remaining emissions mostly from coal combustion in brick–kilns. Dung-cake and forest biomass together account 78% of OM emissions from biomass combustion (Table 3), while they contributed only 28% of total biomass consumption. Open forest fires and lower combustion temperatures during dung-cake combustion are expected to result in PM emissions with larger OM fraction, but need to be verified through measurements.

In India, therefore, biomass combustion is a major source of carbonaceous aerosol emissions, accounting 71% and 76% of total BC and OM emissions, respectively. While, $PM_{2.5}$ emissions are equal in amounts from fossil fuel and biomass combustion, the higher temperatures (1200–1500°C) of fossil fuel combustion results in low carbonaceous aerosols, from coal combustion in particular.

The observed BC emission patterns resemble fuelwood consumption patterns, with higher values in Uttar Pradesh, Bihar and Assam and east-coast (Andhra Pradesh, Orissa and Tamil Nadu) (150 kg km^{-2}) (Fig. 5). The absolute OM emission fluxes are a factor of three–five greater than that of BC emissions. The areas with high dung-cake (Uttar Pradesh, Bihar, Punjab, Haryana) and forest biomass consumption (parts of Madhya Pradesh and Vizianagaram, Vishakapatnam districts in Andhra Pradesh) result in the highest OM emission fluxes (>1000 kg km^{-2}) (Fig. 6). Moderate OM emissions (500–1000 kg km^{-2}) are observed in

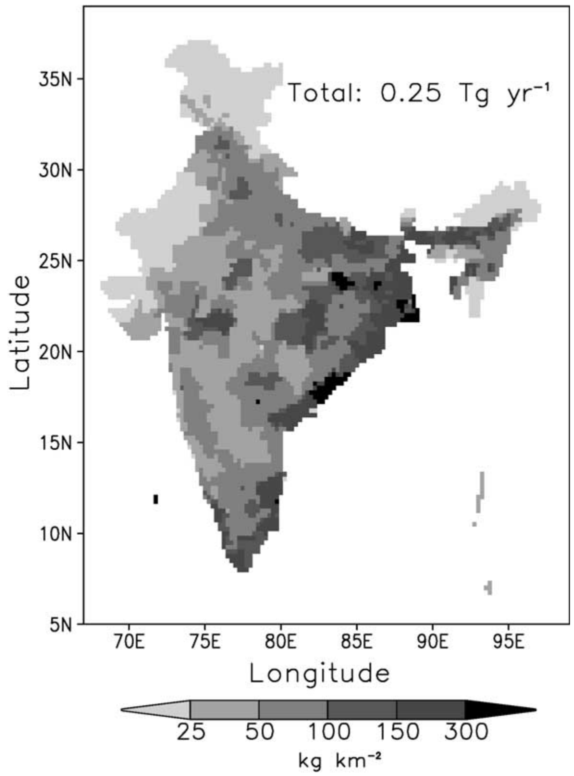

Fig. 5. Spatial distribution of BC emissions from biomass combustion.

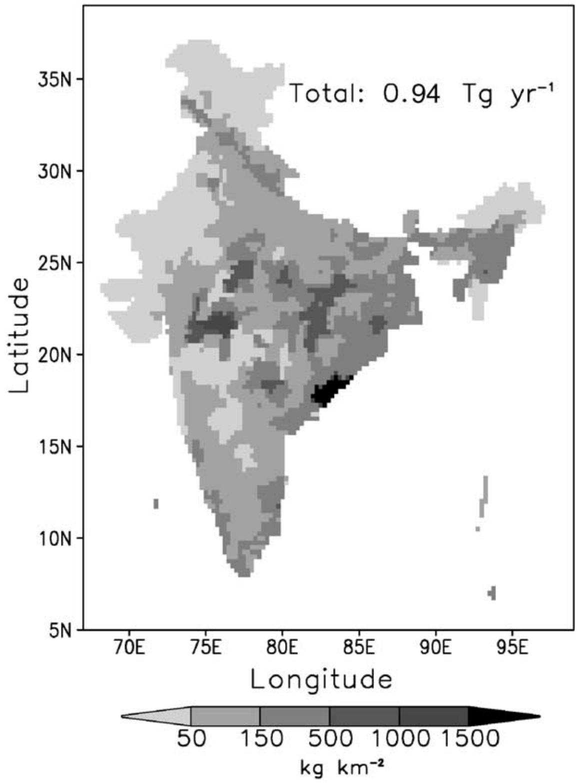

Fig. 6. Spatial distribution of OM emissions from biomass combustion.

south, central and northeast India and low emissions (0–150 kg km^{-2}) are seen in western India and Arunachal Pradesh.

Our estimate of 0.25 Tg BC yr^{-1} from biomass combustion in India is significantly lower than a recent estimate of 0.45 Tg yr^{-1} (Dickerson et al., 2001). This results from the use of different BC emission factors in the two studies for biofuel combustion in cooking stoves, which is the dominant biomass-burning source in India (93% of total). While BC emission factors for Indian cooking stoves are still to be measured, they were derived in the present study from PM emission factors measured for Indian biofuel stoves (Joshi et al., 1989, 1991; TERI, 1987) and BC/PM ratios reported in literature (Rau, 1989) leading to a fuel-consumption-weighted average of 0.48 g kg^{-1}. BC emissions from space heating stoves and fireplaces from which emission factors are typically derived in literature, tend to be higher, because of the higher average fuel burn rate. PM emissions from cooking stoves in India, with a fuel burn rate of 0.4–1.0 kg h^{-1} (Joshi et al., 1989, 1991; Venkataraman and Rao, 2001), are lower than those from space heating stoves and fireplaces, with a fuel burn rate of 1–10 kg h^{-1} (McCrillis et al., 1992; EPA, 1998). To improve these emission estimates, we are involved in studies of measurements of aerosol chemical constituents of climate relevance, using a dilution sampler designed for natural-draught cooking stoves (Venkataraman and Rao, 2001), from a range of stove-fuel systems representative for India.

In the present estimate, emission factors for all biomass types have been refined to represent the BC emissions from biofuels combustion in the domestic cooking stoves. Fuel specific OC/$PM_{2.5}$ ratios (OM emission factors) are applied based on the combustion characteristics, to closely represent the combustion temperatures in Indian cooking stoves and hence resulting emissions. Previous global carbonaceous emission inventories included emissions from biomass combustion from India (Liousse et al., 1996; Penner et al., 1993; Cooke and Wilson, 1996). However, national breakdown of emissions were not given and it is not possible to compare with present estimates.

6.2.3. The "inorganic fraction" of $PM_{2.5}$

The "inorganic fraction" was estimated as the difference between $PM_{2.5}$ and carbonaceous aerosol (sum of "BC and OM") emissions. The low-temperature biomass combustion results in aerosol emissions with high carbonaceous fraction and small amounts of "inorganic fraction".

The "inorganic fraction" emissions from biomass combustion are $0.86\,Tg\,yr^{-1}$ (Table 3), with highest relative contribution from crop waste (34%) followed by fuelwood (26%), forest biomass (21%) and dung-cake (19%). The biomass combustion contributes to 34% of the total "inorganic fraction" emissions ($2.49\,Tg\,yr^{-1}$, *companion paper*) and with balance primarily from coal combustion in power plants. The chemical constituents of "inorganic fraction" from coal and biomass combustion are expected to be different, with coal derived emissions primarily consisting fly ash and biomass derived emissions consisting water-soluble inorganic ions (Rau, 1989; Cachier et al., 1991).

The Vishakapatnam and Vizianagaram districts of Andhra Pradesh have highest forest biomass burning and results in "inorganic fraction" emission fluxes of $1500\,kg\,km^{-2}$. East-coast region has high crop waste consumption and results in emission fluxes of 500–$1000\,kg\,km^{-2}$. The west-coast region experiences low emission fluxes because of low biomass consumption (50–$150\,kg\,km^{-2}$). Once again western Rajastan, Jammu & Kashmir have lowest emissions ($<50\,kg\,km^{-2}$) from lower biofuel consumption. The rest of India has emissions fluxes of 150–$500\,kg\,km^{-2}$.

Our present estimate of "inorganic fraction" emissions from biomass combustion for 1996–1997, a factor of 1.4 higher than previous estimate $0.61\,Tg\,yr^{-1}$ for 1990 (Reddy and Venkataraaman, 2000). Increase in the emissions is because of increase in the biomass consumption (19%) between 1990 and 1996–1997 and refinement of emission factors for all aerosol types.

7. Extrapolation of pollutant emissions to 1998–1999 (INDOEX period)

One of the objectives of present emissions inventory development is to serve as an input to the transport and climate-modelling studies related to the INDOEX campaign. The emissions for 1996–1997 were extrapolated to 1998–1999 (INDOEX period) (Table 5), in proportion to increase in the respective biofuel consumption. However, the emissions from forest biomass burning are assumed to be constant, as there would not be any systematic trend of increase or decrease in the forest fires over a period of time. Spatially resolved ($0.25° \times 0.25°$) SO_2 and $PM_{2.5}$ chemical constituents (BC, OM and "inorganic fraction") emission maps for INDOEX period can be developed by multiplying the grid wise emissions for 1996–1997 with respective growth factors (Table 5).

Table 5
Aerosol and SO_2 emission projections for INDOEX period (1998–1999)

Pollutant	Emissions ($Tg\,yr^{-1}$)		Growth factor
	1996–1997	1998–1999	
Sulphur dioxide	0.32	0.33	1.04
$PM_{2.5}$	2.04	2.10	1.03
Black carbon	0.25	0.26	1.03
Organic matter	0.94	0.97	1.03
"Inorganic fraction"	0.86	0.89	1.03

8. Conclusions

A spatially resolved biomass burning data set, and related emissions of SO_2 and aerosol chemical constituents was constructed for India, for 1996–1997 and extrapolated to the INDOEX period (1998–1999). Sources included biofuels (wood, crop waste and dung-cake) and forest fires (accidental, shifting cultivation and controlled burning). PM emission factors were compiled from studies of Indian cooking stoves and from literature for open burning. BC and OM emissions were estimated from these, accounting for combustion temperatures in cooking stoves. SO_2 emission factors were based on fuel sulphur content and reported literature measurements.

Biofuels accounted 93% of total biomass consumption ($577\,MT\,yr^{-1}$), with forest fires contributing only 7%. This is in contrary to global patterns, where forest fires are the primary and biofuels a negligible contributor. The biofuel-mix varied across different regions, with a national average of 56 : 21 : 23% for fuelwood, crop waste and dung-cake, respectively. The biomass consumption densities were high over the east-coast and north India, and low over central and western India.

Sulphur dioxide emissions were 7% from biomass combustion, compared to 93% from fossil fuel combustion. This is in contrast to previous biomass contribution estimates of 19–23%, and results from more realistic SO_2 emission factors, especially for dung-cake. Dung-cake results in higher SO_2 emissions from its high sulphur content compared to other biomass types.

The biomass combustion in India resulted in $2.04\,Tg\,yr^{-1}$ of $PM_{2.5}$ emissions, equal to that from fossil fuel combustion. Fuelwood was major contributor to particulate emissions from biomass combustion. The $PM_{2.5}$ emission fluxes were high in east-coast and north India. The "inorganic fraction" of $PM_{2.5}$ emissions was $0.86\,Tg\,yr^{-1}$. Water-soluble inorganic ions, rather than mineral ash, are expected to constitute this "inorganic fraction", which must be verified through measurements.

In India, biomass combustion was the major source of carbonaceous aerosol emissions, accounting $0.25\,\mathrm{Tg\,yr^{-1}}$ of BC (72% of total) and $0.94\,\mathrm{Tg\,yr^{-1}}$ of OM (76% of total). The low combustion temperatures in the domestic biomass cooking stoves result in particulate emissions with larger carbonaceous fraction, compared to high-temperature coal combustion. Among biomass, fuel-wood and crop waste were primary contributors to BC emissions, while dung-cake and forest fires were primary contributors to OM emissions.

While emissions from fossil fuel combustion are localised to large point sources (utilities, refineries and petrochemicals, cement and fertilisers) and major cities, emissions from biomass combustion are area sources spread all over India.

The spatial variation in biomass consumption was accounted in estimating emissions. However, rural per capita consumption of biofuels are representative of 1984–1992 and must be updated in future studies. Measurements of emission factors of SO_2, size resolved aerosols and their chemical constituents for Indian cooking stoves are needed to improve the present estimates.

Note: Detailed tables of fuel- and state-wise emissions, and emission maps of SO_2, $PM_{2.5}$, BC, OM and "Inorganic Fraction" are posted on *Aerosol Research Laboratory* website at http://www.iitb.ac.in/~cese/arl/eminv.htm.

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